DEMONSTRATION OF SUBSCALE CERMET FUEL SPECIMEN FABRICATION APPROACH USING SPARK PLASMA SINTERING AND DIFFUSION BONDING

Marvin W. Barnes[1], Dr. Dennis S. Tucker[1], and Kelsa M. Benensky[1,2]

[1]*Materials and Processes Laboratory, NASA Marshall Spaceflight Center, Huntsville, AL 35811,*
marvin.w.barnes@nasa.gov
[2] *Department of Nuclear Engineering, University of Tennessee, Knoxville, TN 37996; (256) 544-2040*

Nuclear thermal propulsion (NTP) has the potential to expand the limits of human space exploration by enabling crewed missions to Mars and beyond. The viability of NTP hinges on the development of a robust nuclear fuel material that can perform in the harsh operating environment (≥ 2500K, reactive hydrogen) of a nuclear thermal rocket (NTR) engine. Efforts are ongoing to develop fuel material and to assemble fuel elements that will be stable during the service life of an NTR. Ceramic-metal (cermet) fuels are being actively pursued by NASA Marshall Space Flight Center (MSFC) due to their demonstrated high-temperature stability and hydrogen compatibility. Building on past cermet fuel development research, experiments were conducted to investigate a modern fabrication approach for cermet fuel elements. The experiments used consolidated tungsten (W)-60vol%zirconia (ZrO_2) compacts that were formed via spark plasma sintering (SPS). The consolidated compacts were stacked and diffusion bonded to assess the integrity of the bond lines and internal cooling channel cladding. The assessment included hot hydrogen testing of the manufactured surrogate fuel and pure W for 45 minutes at 2500 K in the compact fuel element environmental test (CFEET) system. Performance of bonded W-ZrO_2 rods was compared to bonded pure W rods to access bond line integrity and composite stability. Bonded surrogate fuels retained structural integrity throughout testing and incurred minimal mass loss.

I. INTRODUCTION

NASA's goal to conduct exploration missions beyond low-Earth orbit, including manned Mars missions, forces the nation to develop new enabling technologies. Nuclear thermal propulsion (NTP) is a technology innovation that has the potential to enable manned Mars missions. Nuclear thermal rockets (NTRs) utilize nuclear thermal energy to generate propulsive forces and offer a higher specific impulse than traditional chemically propelled spacecraft (liquid engines, solid motors, etc.), which reduces transient times and limits astronaut exposure to space radiation.

Nuclear fuel development is a key challenge for NTP due to the extreme operating conditions of an NTR. Fuel materials must maintain their stability at temperatures above 2500K (2227 °C) in flowing hydrogen while sustaining a fission chain reaction. Ceramic-metal (cermet) fuels that consist of an embedded ceramic fuel particle and a refractory metal matrix have shown viability in past research efforts.[1, 2] Refractory metals such as tungsten (W) and molybdenum (Mo) provide the required structural integrity, hydrogen compatibility, and thermal conductivity at elevated temperatures, while ceramic fuel particles, uranium dioxide (UO_2) or uranium mononitride (UN), generate neutrons to sustain the nuclear chain reaction. Cermet fuels research conducted in the 1960s demonstrated the potential of W-UO_2 cermet fuels by fabricating and testing prototypic fuel elements in a relevant environment. The elements were fabricated by first forming W-UO_2 compacts from blended powder, the compacts were sintered, and then stacked and diffusion bonded to form fuel elements.[3] Using this concept (stacking and bonding compacts), a study was conducted to assess the integrity of a subscale stacked and bonded specimen. Innovative methods were used to fabricate tungsten zirconia (W-ZrO_2) and tungsten deplete uranium dioxide (W-dUO_2) compacts; microscopy and testing in the Compact Fuel Element Environmental Test (CFEET) [4] were used to understand bondline integrity and stability in hydrogen at 2500K.

II. COMPACT FABRICATION

Both W-ZrO_2 and W-dUO_2 compacts were fabricated, however only W-ZrO_2 compacts were used in specimen fabrication (stacking and bonding) and testing. W-dUO_2 compacts are described herein to demonstration the viable of the fabrication process to produce compacts using prototypic cermet materials. W-dUO_2 compacts are schedule for future testing.

Heritage cermet fuels research has established the benefits of coating fuel particles to provide a protective barrier to hydrogen and to generate particle dispersion within the tungsten matrix.[2] As described in section II.A, particle coating was accomplished by blending surrogate ZrO_2 particles (particle size distribution: 180 to 212 microns) or dUO_2 particles (particle size: approximately 175 microns) with tungsten (particle size distribution: 5 to 15 microns) and a binder. The blended material was spark plasma sintered to form dense cylindrical compacts.

II.A. Tungsten Powder Coating

Quantities of W and ZrO_2 or W and dUO_2 were weighed and blended in 100-gram (g) batches. This batch size was chosen for convenience and ease of handling. Each 100-g batch contained approximately 69 g of W and 31 g of ZrO_2 or 54 g of W and 46 g of dUO_2 to achieve a 60-volume percent fuel loading. A small quantity of an organic binder material was added to each batch. Then, each batch was blended in a Turbula® shaker-mixer for approximately 1 hour. The blended material was further processed to ensure that the smaller tungsten particles were bounded to the surface of the larger ZrO_2 or dUO_2 particles.[5] Micrographs of tungsten powder-coated ZrO_2 particles can be seen in figures 1 and 2.
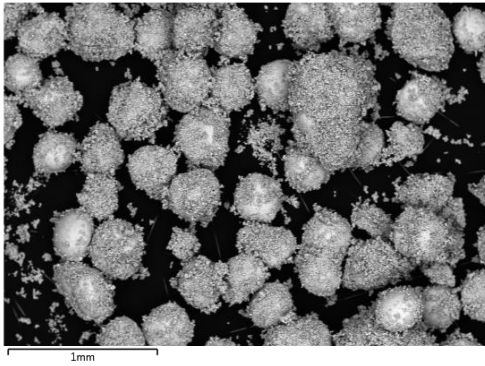
Fig. 1. Tungsten Powder Coated Surrogate Particles 100X
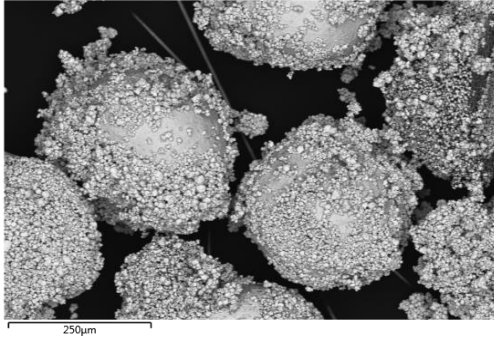
Fig. 2. Tungsten Powder Coated Surrogate Particles 250X

II.B. Spark Plasma Sintering

Using spark plasma sintering (SPS), the blended material was consolidated into dense compacts. To begin the SPS process, blended material was loaded into a 20-mm graphite die and sandwiched between two graphite punches. The loaded graphite die/punch assembly was placed into the SPS system. SPS use the flow of electrical current to elevate the temperature of the material that is being sintered to a pre-programed sintering dwell temperature. For W-dUO_2 compact, sintering was accomplished by increasing the temperature at a rate of 100 °C per minute and pressure at a rate of 20 MPa per minute until the material reached a predetermined sintering temperature and pressure (sintering dwell pressure = 50 MPa for all specimens). The sintering temperature and pressure were maintained for 20 minutes; then, the material was allowed to cool at a rate of 20 °C per minute. The sintering dwell temperature of the dUO_2 compacts was varied as shown in table 1. Sintering dwell temperature was varied to understand the relationship between sintering temperature and the mechanical properties (density) of the sintered compact.

TABLE I. Sintering Parameters for dUO_2 Compacts

No. of Specimens	Sintering Dwell Temperature (°C)	Sintering Dwell Temperature (MPa)
1	1600	50
4	1700	50
4	1750	50
5	1800	50
1	1850	50

The same ramp rates used for dUO_2 compacts fabrication were applied to the ZrO_2 compacts, however the sintering dwell temperature was not varied as there was no interest in observing the effects of sintering dwell temperature on density. Experimentation found 1773K (1500 °C) to be the optimal sintering dwell temperature for form nearly theoretical dense ZrO_2 compacts.

II.C. Tungsten Depleted Uranium Dioxide Wafers
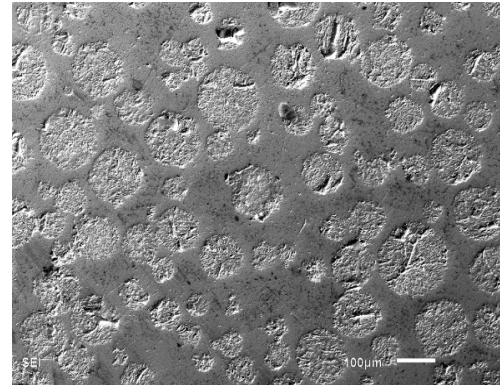
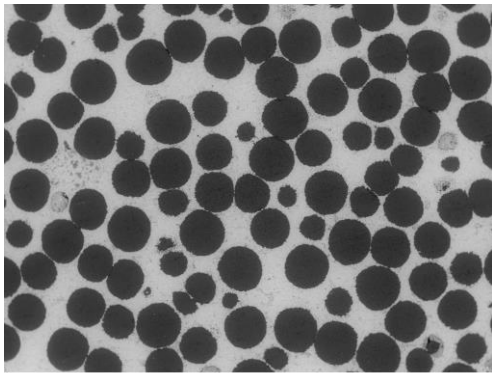

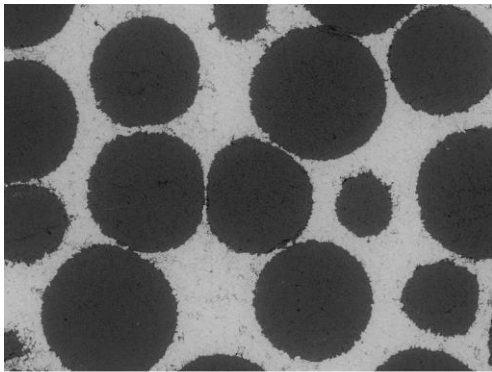**Fig. 3.** W-60vol%dUO2 microstructure scanning electron microscope image 100X
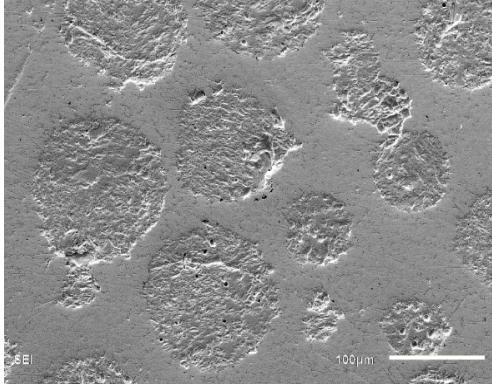
Fig. 4. W-60vol%dUO2 microstructure scanning electron microscope image 250X

II.D. Tungsten Depleted Uranium Dioxide Wafers

Fig. 5. W-60vol%dZrO2 microstructure scanning electron microscope image 100X

Fig. 6. W-60vol%dZrO2 microstructure scanning electron microscope image 250X

III. SPECIMEN FABRICATION

Specimen fabrication was accomplished by stacking ZrO_2 compacts and hot isotactic pressing (HIP) to diffusion bond compacts into a solid specimen that was approximately 5 cm (2 inches) long and 1.6 cm (0.625 inches) in diameter.

Fig. 7. W-60vol%dZrO2 compacts stacked

Fig. 8. W-60vol%dZrO2 compacts HIP diffusion bonded

IV. TESTING & RESULTS

The specimen was exposed to hydrogen in the CFEET for forty-five minutes at 2500K (2227 °C).

Results from hot hydrogen testing were favorable with minimal degradation and mass loss observed in the tested specimen. The bondlines were not compromised, and no debonded was noted.

II. CONCLUSIONS

Additional testing is required to optimize the process and demonstrate repeatability. Further research is needed to understand the feasibility of stacking and bonding prototypic materials (dUO_2). Future research will focus on the stability of $W/60\%voldUO_2$ compacts in hot hydrogen and demonstrating the fabrication process with $W-dUO_2$ and $Mo-dUO_2$ cermets.

ACKNOWLEDGMENTS

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